

Linac-Ring Type ϕ Factory for Basic and Applied Researches

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In this paper, main parameters for linac-ring type collider desinged for producing ϕ particles copiously are estimated and potential of this machine in particle physics researches is investigated. Moreover, parameters for free electron laser and synchrotron radiation obtained from electron linac and positron ring, respectively, are determined and applications of these radiations are summarized.

I. INTRODUCTION

The center of mass energy \sqrt{s} needed to produce ϕ particles is enough to be about 1 GeV. In this study main parameters of two linac-ring type collider options are given: one with 125 MeV linac electron beam and 2 GeV positron beam, another with 250 MeV linac electron beam and 1 GeV positron beam. Main reason for designing collider as linac-ring type machine is the possibility to increase luminosity by of one or two orders with respect to standart ϕ factories. Today the highest luminosity among the standard (ring-ring type) ϕ factories is owned by $DA\phi NE$ with $L = 5 \times 10^{32} cm^{-2} s^{-1}$ [1]. Proposed collider will give opportunity to reach luminosity $\sim 10^{34} cm^{-2} s^{-1}$.

Great number of neutral and charged K mesons ($> 10^{11}$ per working year), produced as a result of decays of ϕ mesons, can be investigated. The importance of K mesons study is obvious: for example, the CP-violation (matter-antimatter asymmetry) was observed and established in neutral K mesons' decays.

Proposed accelerator complex will give opportunity to perform a large spectrum of applied researches: positron ring can be used as the third generation synchrotron radiation (SR) source and Free Electron Laser (FEL) can be constructed on the base of main electron linac.

In following section we present general overview of linac-ring type ϕ factory. Main parameters of proposed machine are estimated in Section III. Then, in Section IV physics search potential of the collider is briefly discussed. Parameters of SR and FEL photon beams are estimated in Sections V and VI, respectively. We also list the possible applications of these beams in different fields of science and technology in Section VII. Finally, in Section VIII we give some concluding remarks.

II. GENERAL OVERWIEV

The general scheme of proposed complex is given in Fig. 1. Electrons accelerated in main linac up to energies 250 (125) MeV are forwarded to detector region where they collide with positrons from main ring or turned out to undulator region where FEL beam is produced.

On the other side electrons, accelerated in small linac, are forwarded to conversion region where positron beam is produced. Then, positrons are accumulated in booster and after some beam gymnastics are forwarded to the main ring and accelerated up to energies 1(2) GeV. Wigglers installed in two regions will provide SR for applied researches.

III. MAIN PARAMETERS OF LINAC-RING TYPE ϕ FACTORY

The usage of linac-ring type colliders as a particle factories is widely discussed during the last decade. Below we list some proposals with corresponding references:

- i) B Factory [2],
- ii) c- τ Factory [3],
- iii) Z Factory [4].

The main advantages of linac-ring type machines are: the possibility to achieve essentially higher luminosities with respect to standard ring-ring type particle factories and asymmetric kinematics. Of course, LR type ϕ factory is most compact one because of lowest center-of-mass energy.

Main parameters of proposed machine are given in Table I for two different choices of electron and positron beam energies. Below we present several illuminating notes.

Electron bunches accelerated in main linac are used only once for collisions. On the other hand, positron bunches have to be used numerously, therefore, the stability of positron beam is very important. The condition of stability is given by

$$n_{e-} = 8.7 \times 10^8 \cdot E_{e+} [GeV] \cdot (\sigma [\mu m])^2 \cdot (\beta^* [cm])^{-1} \cdot \Delta Q \quad (1)$$

where n_{e-} is number of particles in electron bunch, E_{e+} is positron beam energy, σ is transverse size of beams and β^* is amplitude function at the collision point, ΔQ is tune shift caused by collision. Emphrically, $\Delta Q \leq 0.06$ for lepton beams stored in rings. In principle, this upper limit taken from experiments done in usual ring-ring type e^+e^- colliders can be higher for linac-ring type machines. In this paper we use the conservative value $\Delta Q \leq 0.06$.

Synchrotron radiation resulted from bending magnets used in ring type accelerators causes to decrease in beam energy. Energy loss happened as a result of this radiation in every tour is given by

$$\Delta E_{e+} [MeV] = 0.0885 \cdot (E_{e+} [GeV])^4 \cdot (R [m])^{-1} \quad (2)$$

where R is radius of the ring.

The fractional energy loss of electrons in positron beam field is given by

$$\delta = (n_{e+} [10^{12}])^2 \cdot (\sigma_z [cm])^{-1} \cdot (\sigma_x [\mu m] \cdot \sigma_y [\mu m])^{-1} \cdot E_{e+} [TeV] \quad (3)$$

where n_{e+} is number of particles in one positron bunch, $\sigma_{x,y}$ are vertical and horizontal transverse sizes of beam at the collision point (in our case $\sigma_x = \sigma_y = \sigma$), σ_z is the bunch length.

Electron current is given by

$$I_{e-} [mA] = 1.6 \times 10^{-19} \cdot n_{e-} \cdot f \quad (4)$$

where f is the collision frequency. Positron current in the ring is

$$I_{e+} [A] = 1.6 \times 10^{-19} \cdot k \cdot n_{e+} \cdot (c/2\pi R) \quad (5)$$

where k is the number of positron bunches in the ring and c is the speed of light.

IV. PHYSICS SEARCH POTENTIAL

Quantum numbers of ϕ mesons produced as a resonance in e^+e^- collisions are $I^G(J^{PC}) = 0^-(1^{--})$. Mass is $m_\phi = 1015.413 \pm 0.008$ MeV and total decay width is $\Gamma = 4.43 \pm 0.05$ MeV [5]. Fundamental decay channels and branching ratios are given in Table II.

Since deviation of the center-of-mass energy of e^+e^- collisions is smaller than the total decay width of ϕ meson, cross-section in the ϕ resonance region can be taken as

$$\sigma = (12\pi/m^2) \cdot (\Gamma_c/\Gamma) \simeq 4.4 \times 10^{-30} cm^2 \quad (6)$$

In the proposed complex $4.4 \times 10^{11} \phi$ meson, $2.2 \times 10^{11} K^+ K^-$ pairs and $1.5 \times 10^{11} K_L^0 K_S^0$ pairs can be produced in a working year ($10^7 s$). Fundamental problems of particle physics such as CP violation, rare decays of K mesons etc. can be investigated with highest statistics. Moreover, kinematical asymmetry can be advantageous for measuring neutral K meson's oscillations and CP violation parameters. Detailed analysis of physics search potential will be done in forthcoming publications.

V. SYNCHROTRON RADIATION FACILITY

Charged particles emit electromagnetic radiation when they accelerated in the circular orbit. This radiation is called synchrotron radiation. Synchrotron radiation is usually disturbing phenomenon since it causes to loss of energy of particles. However, synchrotron radiation has very wide applications since it covers a wide spectrum including x-ray region. Energy loss with synchrotron radiation is proportional to γ^4 , where γ is the Lorentz factor. To change the spectrum of the radiation, either synchrotron ring radius or energy of the positrons moving on the ring should be changed, but both of them are not practical methods. Therefore, photons with higher energy can be produced by using a series of alternating directional equal dipole magnets, called wiggler. By inserting wigglers on the straight parts of the main ring of ϕ factory, one can produce synchrotron radiation for applied researches.

When one thinks of whole wiggler, every pole end is designed to effect particle path neutrally. Photon flux is proportional to number of the magnet poles. Strength parameter of the wiggler magnet is given by

$$K = 0.934 \cdot B_0[T] \cdot \lambda_p[cm] \quad (7)$$

where λ_p is the length between sequential same directional magnet poles. B_0 is the maximum magnetic field strength on midplane axes and its value for hybrid permanent magnet system is approximately (for $g \leq \lambda_p$)

$$B_0 \simeq B_m \exp\left[-\frac{g}{\lambda_p}\left(b - c\frac{g}{\lambda_p}\right)\right] \quad (8)$$

where g is vertical distance between magnets, B_m is peak value of magnet's field, b and c are constants related to used permanent magnets. If one use SiCo type magnet: $B_m = 3.33$ Tesla, $b = 5.47$ and $c = 1.8$ [6]. Fig. 2 shows g dependence of strength parameter of the wiggler for two values of λ_p .

Power emitted by the wiggler is given by

$$P[kW] = 0.632 \cdot L[m] \cdot I_{e+}[A] \cdot (E_{e+}[GeV])^2 \cdot (B_0[T])^2 \quad (9)$$

where L is the total length of wiggler. The power of the designed wiggler's radiation with respect to g is shown in Fig. 3.

Spectral flux and spectral central brightness are given by

$$I_F[phot./sec \cdot mrad \cdot 0.1\%bandw] = 2.458 \cdot 10^{10} \cdot 2N \cdot I_{e+}[mA] \cdot E_{e+}[GeV] \cdot \frac{E}{E_c} \int_{E/E_c}^{\infty} K_{5/3}(\eta) d\eta \quad (10)$$

and

$$I_B[phot./sec \cdot mrad^2 \cdot 0.1\%bandw] = 1.325 \cdot 10^{10} \cdot 2N \cdot I_{e+}[mA] \cdot E_{e+}^2[GeV]^2 \cdot \left(\frac{E}{E_c}\right)^2 K_{2/3}\left(\frac{E}{E_c}\right), \quad (11)$$

where E and E_c are photons energy and critical energy, respectively. Fig. 4 and Fig. 5 present the spectral flux and central brightness with respect to photon energy for three different g values. Critical photon energy is defined by

$$E_c[keV] = \hbar\omega_c = 0.665 \cdot (E_{e+}[GeV])^2 \cdot B[T] \quad (12)$$

Main parameters of SR facility for two options are given in Table III.

VI. FREE ELECTRON LASER FACILITY

Free Electron Laser (FEL) is a mechanism to convert some part of the kinetic energy of relativistic electron beam into tunable, highly bright and monochromatic coherent photon beam by using undulators inserted in linear accelerators

or synchrotrons [7]. Relativistic electron beam oscillates on a sinusoidal path with the help of a undulator magnet which has an oscillating magnetic field between its poles. As a result FEL beam is produced (see, Fig.6.)

Wavelength of the obtained FEL beam is dependent on energy of electron beam, period of undulator poles and undulator's K parameter

$$\lambda_{FEL} = \frac{\lambda_p}{2\gamma_e^2} \left(1 + \frac{K^2}{2}\right) \quad (13)$$

where λ_p is period length of undulator, γ_e is Lorentz factor of the electron beam. Undulator parameter, K, is given by Eqn. (7). For undulator $K \simeq 1$ and especially the first harmonic contributes into the radiation. Laser wavelength and energy for plane undulator in terms of practical units are given as

$$\lambda_{FEL}[\text{\AA}] = 13.056 \frac{\lambda_p[\text{cm}]}{(E_{e-}[\text{GeV}])^2} \left(1 + \frac{K^2}{2}\right) \quad (14)$$

and

$$E_{FEL}[\text{eV}] = 950 \frac{(E_{e-}[\text{GeV}])^2}{\lambda_p[\text{cm}](1 + \frac{K^2}{2})} \quad (15)$$

Main parameters of FEL facility for two options are given in Table IV.

Magnetic field strength between poles of plane undulators is given by Eqn. (8). For using thereafter, magnetic field is estimated to be 1.48 kG with $b = 5.47$, $c = 1.8$, $\lambda_p = 33 \text{ mm}$ and $g = 25 \text{ mm}$. With these values, strength parameter of undulator can be obtained from Eqn.(7) as $K = 0.456$.

Flux of FEL beam as a function of energy is given as follows [8]

$$I_{FEL} = 1.74 \cdot 10^{14} N^2 (E_{e-}[\text{GeV}])^2 I[A] F_n[K] f(n\nu_n) \quad (16)$$

where

$$F_n[K] = \xi n^2 [J_{(\frac{n-1}{2})}(n\xi) - J_{(\frac{n+1}{2})}(n\xi)]^2, \quad \xi = \frac{1}{2} \frac{K^2}{1 + K^2} \quad (17)$$

and

$$f(\nu) = \left(\frac{\sin \nu/2}{\nu/2}\right)^2, \nu_n = 2\pi N \frac{n\omega_1 - \omega}{n\omega_1}, n = 1, 3, 5... \quad (18)$$

Here J_n is n-th order cylindrical Bessel function, $\omega_1 = E_{FEL}/\hbar$ is the frequency of the first harmonic radiation, N is the number of undulator poles and n is the order of harmonics. Fig. 7 shows the dependence of FEL flux on photon energy for $E_{e-} = 250 \text{ MeV}$ option. Here peaks are placed at odd harmonics and maximum values of fluxes are $7.56 \cdot 10^{13}$, $1.08 \cdot 10^{13}$ and $9.45 \cdot 10^{11}$ for $n = 1, 3$ and 5 , respectively. Obtained averaged brightness values of photon beam are given in Table IV.

VII. APPLICATIONS FIELDS OF SYNCHROTRON RADIATION AND FREE ELECTRON LASERS

Synchrotron radiation sources and free electron lasers have a rich spectrum of applications (see, for example, [9]) both in scientific researches and industry. Part of them are listed below:

- Atomic and molecular spectroscopy,
- Spectroscopy of atomic and molecular clusters,
- Solid state spectroscopy,
- Physics and chemistry of surfaces and thin films,
- Photochemical processes,
- Biological structure and dynamics,
- Materials and surface processing,
- Multilayer magnetic films,
- The electronic structure of semiconductors,
- Heavy fermion materials and high temperature superconductors,
- Dynamics of catalytic reactions.

Proposed SR source will cover a photons wavelengths $\lambda \geq 0.1 \text{\AA}$, whereas FEL will produce a laser beam with $\lambda \approx (760 - 3000) \text{\AA}$. Due to appropriate modifications of wiggler or undulator parameters these regions may be extended. Moreover there is also possible option of inserting undulator in the positron ring to obtaining FEL beam. All these topics will be considered in forthcoming publications.

VIII. CONCLUSION

In this paper we show that sufficiently high luminosities can be achieved at linac-ring type ϕ factory. Then, the proposed complex will give opportunity to make a wide spectrum of applied and technological researches. In this sense linac-ring type ϕ factory should be considered as candidate for the first step of National Accelerator Laboratory due to its compactness and usefulness.

IX. ACKNOWLEDGEMENTS

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FIG. 1. The general scheme of the proposed complex.

FIG. 2. The g dependence of strength parameter for $\lambda_p = 33$ mm (Dashed line) and $\lambda_p = 132$ mm (Solid line).

FIG. 3. The g dependence of the SR power.

FIG. 4. Spectral flux of the SR. Solid line: $g=30$ mm, Dashed line: $g=25$ mm, Dot-dashed line: $g=20$ mm.

FIG. 5. Spectral central brightness of the SR. Solid line: $g=30$ mm, Dashed line: $g=25$ mm, Dot-dashed line: $g=20$ mm.

FIG. 6. Schematic view of FEL process.

FIG. 7. Flux of FEL beam.

TABLE I. Main parameters of the ϕ factory

Electron beam energy (MeV)	125	250
Positron beam energy (MeV)	2000	1000
Center of mass energy (MeV)	1000	1000
Radius of ring (m)	50	30
Acceleration gradient (MV/m)	12.5	12.5
Lenght of main linac (m)	10	20
Number of particles in electron beam (10^{10})	0.04	0.02
Number of particles in positron beam (10^{10})	10	20
Collision frequency, f (MHz)	30	30
Number of bunches in ring, k	32	19
Electron current (mA)	1.92	0.96
Positron current (A)	0.96	0.48
Energy loss /turn, ΔE_{e^+} (MeV)	0.03	0.003
Fractional energy loss of the electrons, δ (10^{-4})	2	1
Beam size at the collision point, $\sigma_{x,y}$ (μm)	1	1
Beta function at IP, $\beta_{x,y}$ (cm)	0.25	0.25
Bunc length, σ_z (cm)	0.1	0.1
Luminosity, L ($10^{34} cm^{-2} s^{-1}$)	$\simeq 1$	$\simeq 1$

TABLE II. Comparison of event numbers in DAΦNE and proposed collider

Decay channels	Branching ratios	N (DAΦNE)	N (LR type ϕ Factory)
$K^+ K^-$	0.495	$1.1 \cdot 10^{10}$	$2.2 \cdot 10^{11}$
$K_L^0 K_s^0$	0.344	$7.6 \cdot 10^9$	$1.5 \cdot 10^{11}$
$\rho\pi$	0.155	$3.4 \cdot 10^9$	$6.9 \cdot 10^{10}$
$\eta\gamma$	$1.26 \cdot 10^{-2}$	$2.8 \cdot 10^8$	$5.6 \cdot 10^9$
$\pi^0\gamma$	$1.31 \cdot 10^{-3}$	$2.9 \cdot 10^7$	$5.8 \cdot 10^8$
$e^+ e^-$	$2.99 \cdot 10^{-4}$	$6.6 \cdot 10^6$	$1.3 \cdot 10^8$
$\mu^+ \mu^-$	$2.5 \cdot 10^{-4}$	$5.6 \cdot 10^6$	$1.1 \cdot 10^8$
$\eta e^+ e^-$	$1.3 \cdot 10^{-4}$	$2.9 \cdot 10^6$	$5.8 \cdot 10^7$
$\pi^+ \pi^-$	$8 \cdot 10^{-5}$	$1.8 \cdot 10^6$	$3.6 \cdot 10^7$
$\eta'(958)\gamma$	$1.2 \cdot 10^{-4}$	$2.7 \cdot 10^6$	$5.4 \cdot 10^7$
$\mu^+ \mu^- \gamma$	$2.3 \cdot 10^{-5}$	$5.1 \cdot 10^5$	$1.0 \cdot 10^7$

TABLE III. Main parameters of SR facility

Energy (GeV)	1	2
Maximum magnetic field (T)	1.054	1.054
Current (A)	0.976	0.488
Period (cm)	13.2	13.2
Gap (mm)	30	30
Total length (m)	2.112	2.112
Total radiated power (kW)	1.44	2.90
Critical energy, E_c (keV)	0.700	2.804
Wiggler parameter	12.99	12.99
Spectral flux ($Phot/s \cdot mrad \cdot 0.1\%bandw$)	4.96×10^{14}	5.00×10^{14}
Spectral central brightness ($Phot/s \cdot mrad^2 \cdot 0.1\%bandw$)	4.95×10^{14}	9.98×10^{14}

TABLE IV. Main parameters of FEL facility.

	$E_e = 125 MeV$	$E_e = 250 MeV$
Photon energy (eV)	4.07	16.30
Laser wavelength (\AA)	3044	761
Beam current (mA)	1.92	0.96
Particle per bunch (10^{10})	0.04	0.02
Repetition frequency (MHz)	30	30
Averaged laser beam power (W) for $L = 10\ m$	$4.18 \cdot 10^{-3}$	$8.36 \cdot 10^{-3}$
Flux ($Phot/(s \cdot mrad \cdot 0.1\%bandw)$)	$3.78 \cdot 10^{13}$	$7.56 \cdot 10^{13}$
Averaged brightness ($Phot/(s \cdot mrad^2 \cdot 0.1\%bandw)$)	$2.91 \cdot 10^{11}$	$5.81 \cdot 10^{11}$

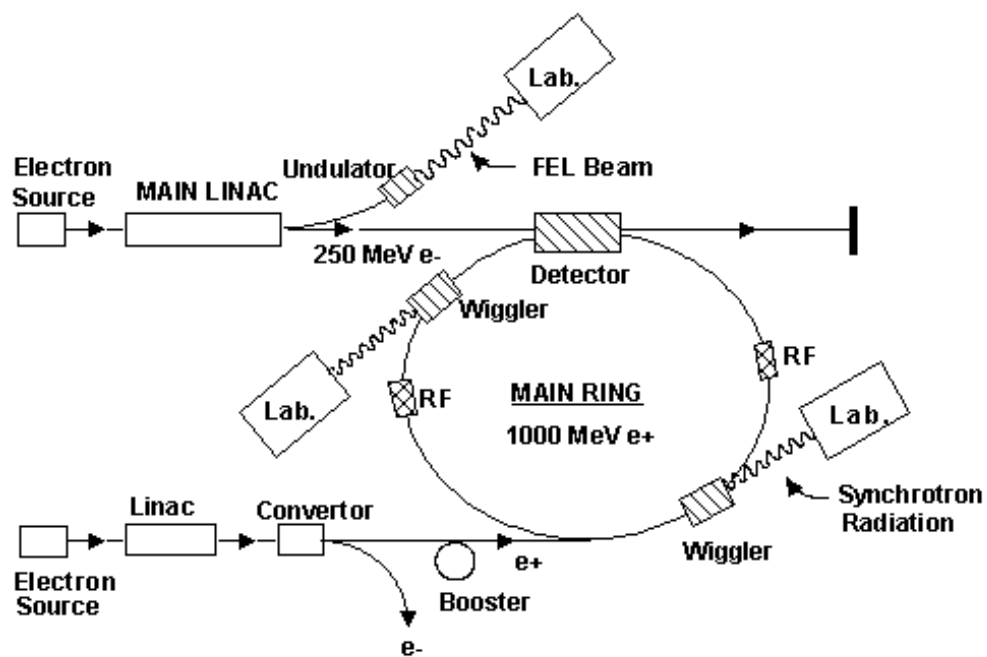


FIG. 1

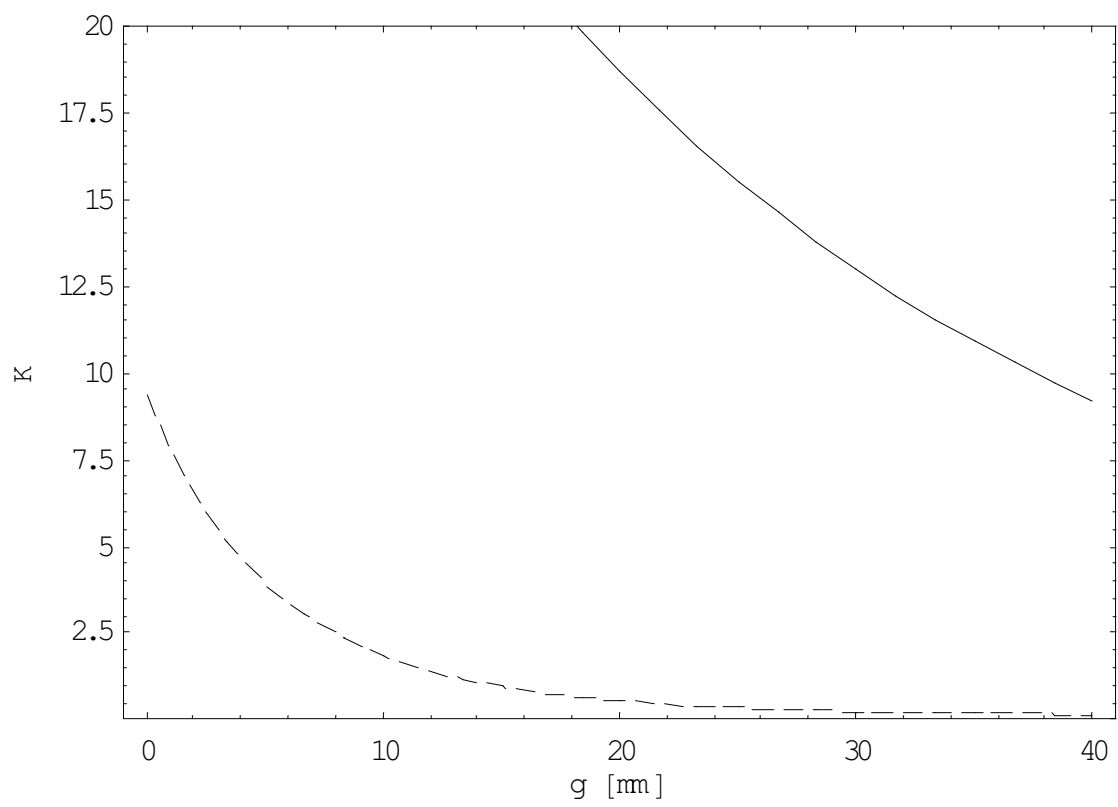


FIG. 2

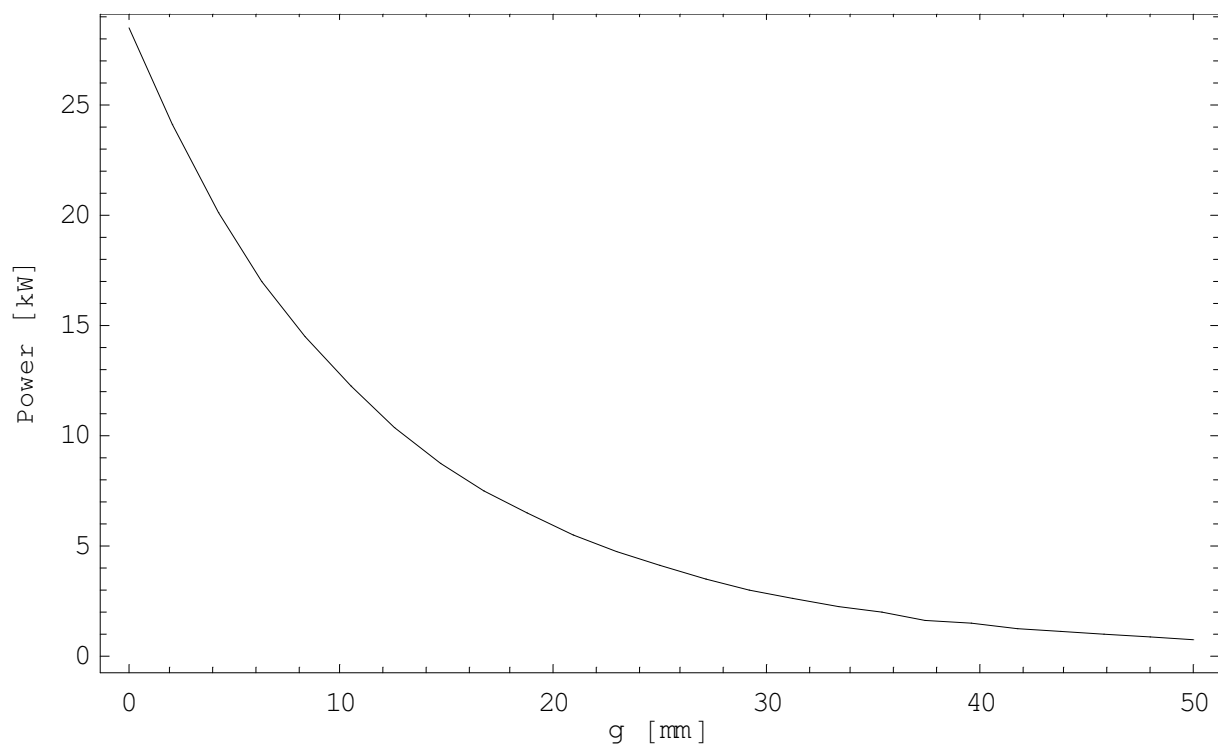


FIG. 3

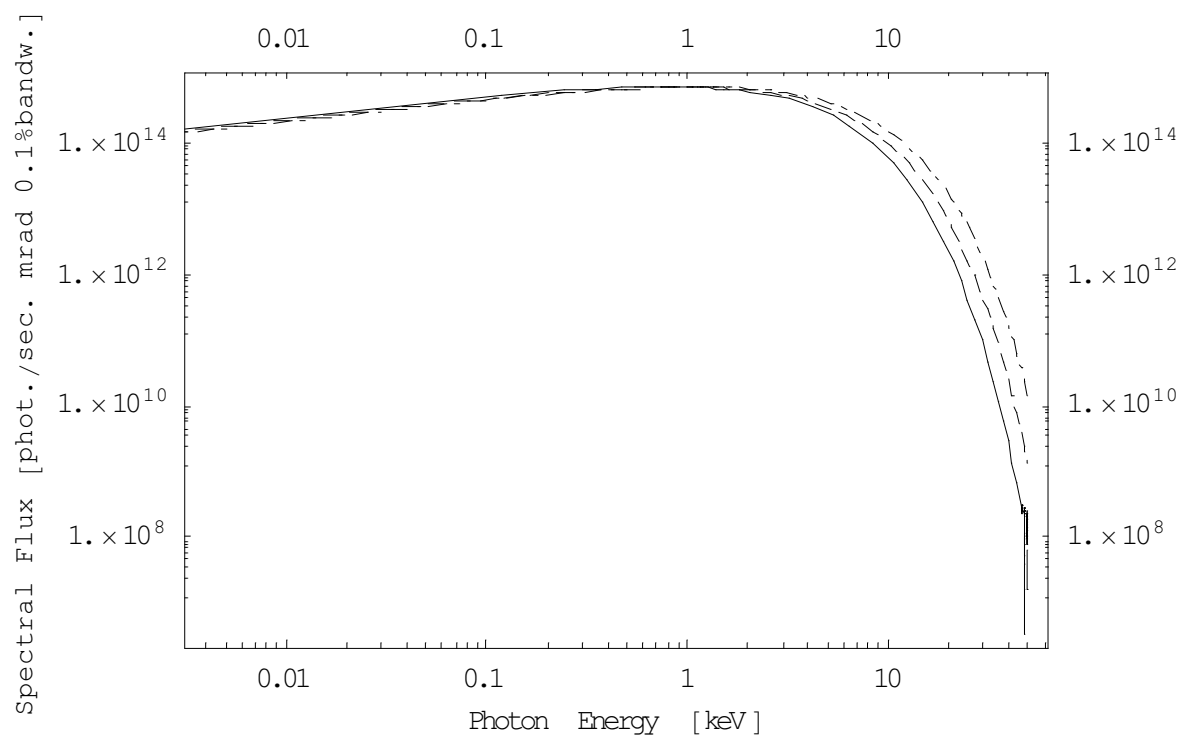


FIG. 4

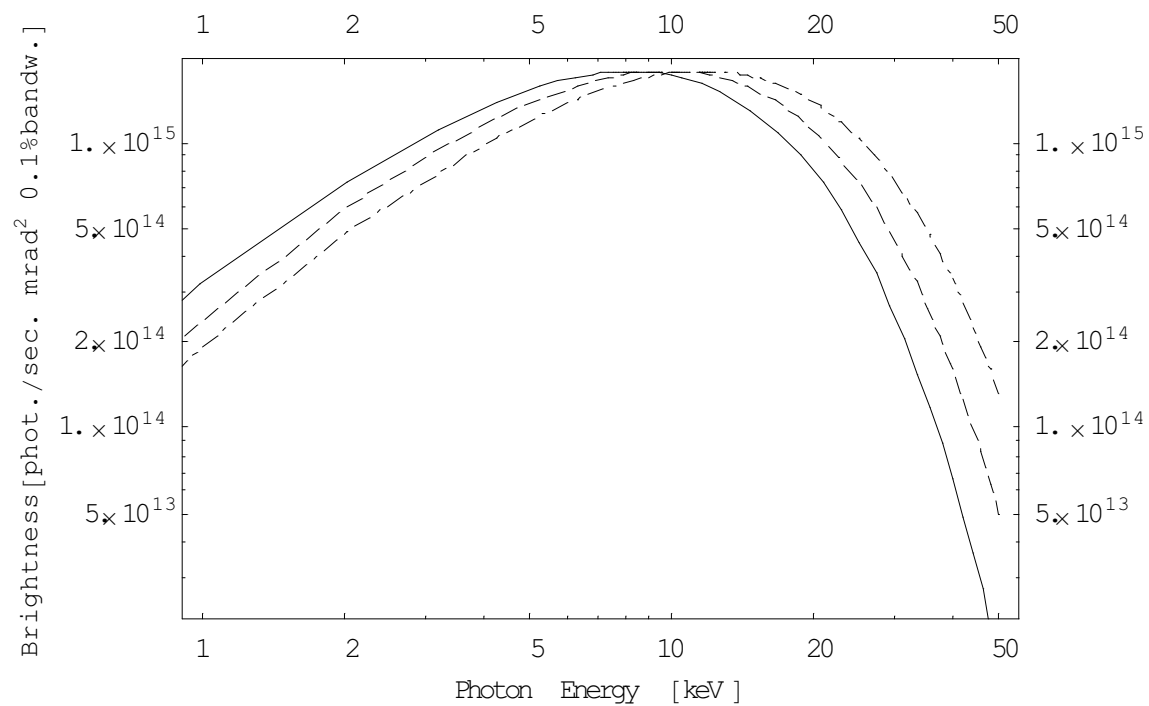


FIG. 5

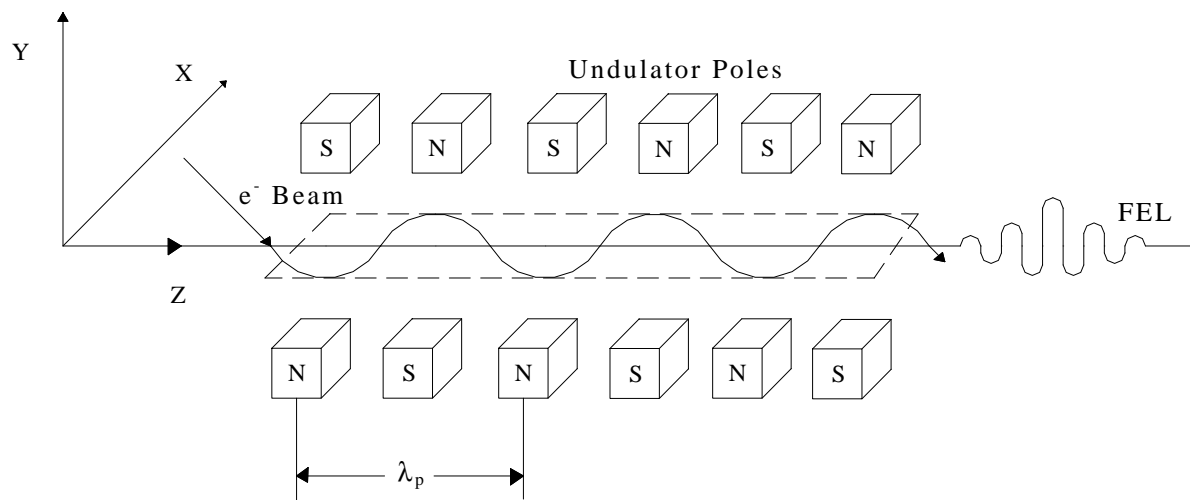


FIG. 6

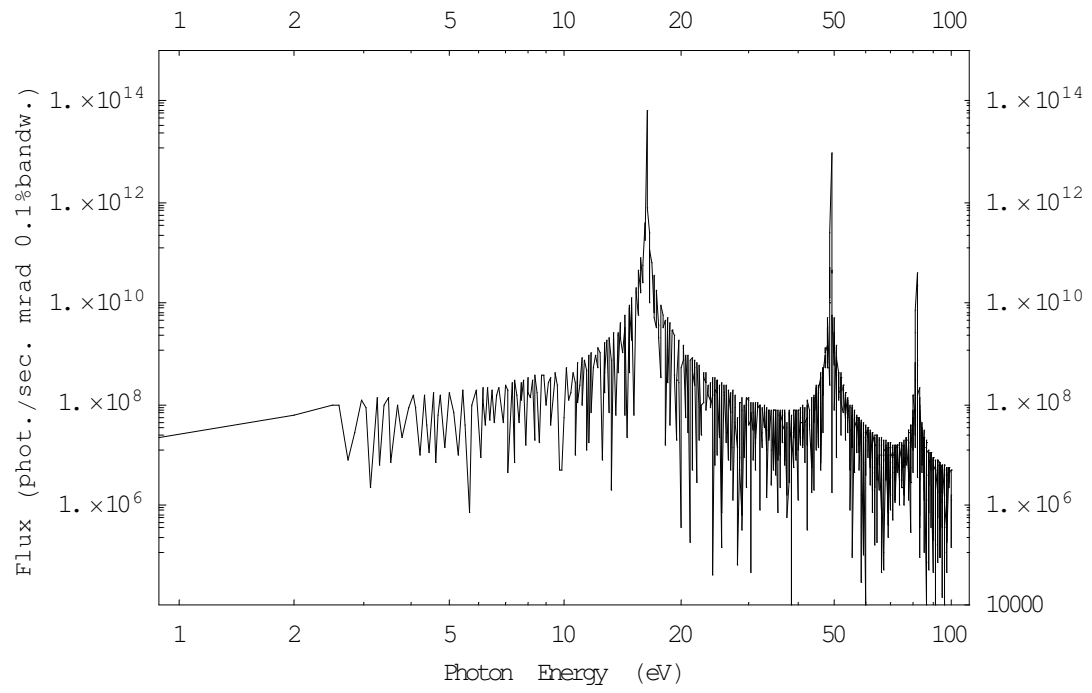


FIG. 7